Power Harvesting From Vibration Using Magnetostrictive Materials

POWER HARVESTING FROM VIBRATION USING MAGNETOSTRICTIVE MATERIALS

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ABSTRACT

The paper addresses the problem of vibration-to-electric energy conversion using magnetostrictive materials. An overview of both theoretical and experimental results of the study of performance of the magnetostrictive electric generator (MEG) which was built at Chalmers University of Technology is presented. An inverse dynamics based algorithm has been proposed for modeling and for optimizing of generator design. The algorithm was implemented in Matlab/Simulink and used for dynamic analysis of the considered controlled magnetoelastic electromechanical system under different periodic excitations of its hosting structure. Both simulation results and experimental data have confirmed functionality of the designed MEG using giant magnetostrictive material Terfenol-D.

1. INTRODUCTION

The study of magnetostriction began in 1842 when James P. Joule first observed that a sample of iron changes its length when magnetized. The term magnetostriction refers to any change in dimension of a magnetic material caused by a change in its magnetization. The Joule magnetostriction is commonly employed in actuator and sensor applications [1-4]. Because magnetostriction is an inherent property of magnetic materials, it does not degrade over time as can be the case with some piezoelectric substances. Furthermore, newer magnetostrictive materials provide strains, forces, energy densities, and coupling coefficients which compete advantageously with more established transducer technologies such as those based on piezoelectric materials.

In the last few years, there has been a surge of research in the area of power harvesting for developing alternative power sources for different applications [5]. Many proposed power harvesting systems employ a piezoelectric component to convert the mechanical energy to electrical energy [5-15]. The major limitation facing researchers in the field of power harvesting revolve around the fact that the power generated by piezoelectric materials is far too small to power most electronics. While piezoelectric materials are now major method of harvesting energy [5], other methods do exist; for example, methods based on Villari effect of magnetostrictive materials [1, 16, 17]. Novel magnetostrictive materials are probably the most prospective materials for vibration-to-electric energy conversion since they have high energy density and very high electromechanical coupling effect. Methods of increasing the amount of energy generated by power harvesting device and developing new and innovative methods of accumulating the energy are the key technologies that will allow power harvesting to become a source of power for portable electronics, wireless sensors and other microelectromechanical systems.

Operation of power harvesting devices and other transducers that use magnetostrictive materials is based on dynamic interaction between magnetic and electric fields, inherent elastic properties of active material and mechanical external loads. To be able to analyze the energy transduction processes, design and optimize the performance of magnetostrictive power harvesting devices and other magnetostrictive transducers, they must be considered as complex magnetoelastic electromechanical systems.

The proposed paper is in the field of applications of giant magnetostrictive materials for power harvesting from vibration, namely vibration-to-electric energy conversion. The problems of mathematical modeling and design of magnetostrictive electric generators are considered. A mathematical model and an inverse dynamics based algorithm have been developed for computer simulation of performance of a MEG integrated into a vibrating structure. The algorithm was implemented in Matlab/Simulink with user friendly interface. A physical prototype MEG and a test rig were built for experimental study of transduction of mechanical energy in vibrating structures into electrical energy using Terfenol-D rod as active material. Both simulation results and experimental data have confirmed functionality of the designed MEG.

2. FUNDAMENTALS OF MAGNETOSTRICTIVE ELECTRIC GENERATORS

Magnetostriction is a transduction process where magnetic energy is converted to mechanical energy. It is called the *Joule effec*t (James Prescott Joule, 1818-1889), and is the most common magnetostrictive mechanism employed in magnetostrictive actuators. Magnetostrictive materials exhibit a change in dimension when placed under a magnetic field. This is a result of reorientation of the magnetic domains, which produces internal strains in the material. The internal strains cause a change in length which can be controlled by the magnetic field. Schematic representation of Joule effect is depicted in Fig. 1.

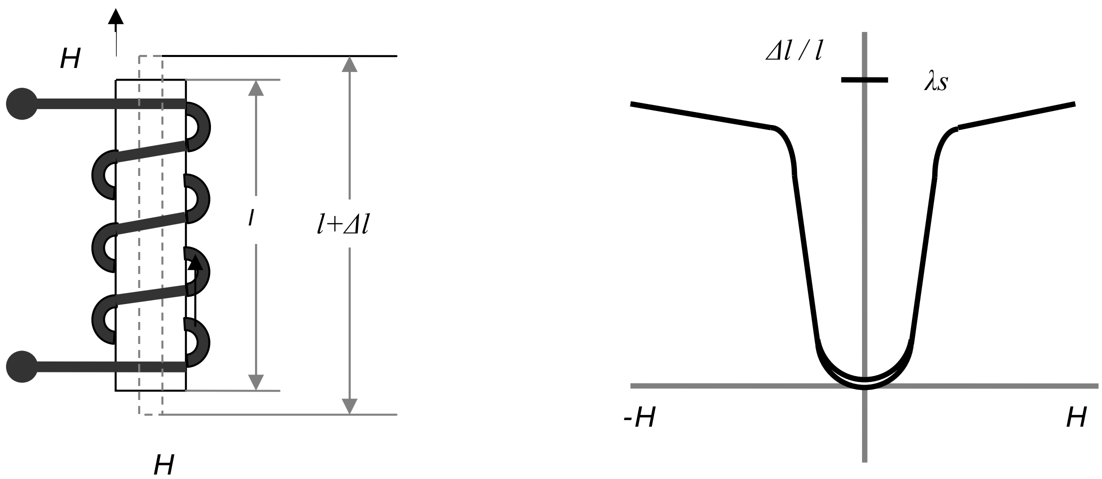

Figure 1. Schematic representation of the Joule effect.

There exists also an inverse process in magnetostrictive samples where mechanical energy is converted to magnetic energy. That is, by applying a mechanical stress to a magnetostrictive material, the magnetization along the direction of the applied stress of the material varies due to the magnetostrictive effect. The flux variation obtained in the material can be used to induce an electromotive force in a coil surrounding the material. This process in magnetostrictive materials is called the *Villari effect* and is used in magnetostrictive sensors. Direct and inverse magnetostrictive effects applicable to actuator and sensor modes of operation are summarized in Table 1, while constructive details of such designs can be found in [1, 18].

Direct Effects	Inverse Effects
Joule Effect Change in sample dimensions in the direction of the applied field	*Villari Effect* Change in magnetization due to applied stress
ΔE effect Magnetoelastic contribution to magnetocrystilline anisotropy	Magnetically induced changes in the Elasticity
Wiedemann effect Torque induced by helical magnetic field	*Matteucci effect* Helical anisotropy and *emf* induced by a torque
Magnetovolume effect Volume change due to magnetization (most evident near the Curie temperature)	*Nagaoka-Honda effect* Change in the magnetic state due to a change in the volume

Table 1. Magnetostrictive effects and their inverse.

Giant magnetostriction was discovered in the basal planes of rare earth metals (Tb - terbium, Dy - dysprosium). The strains were about 0.6% (6000 ppm) at the temperature of 150 K. The giant magnetostrictive materials are available in several alloys like Terfenol-D, Galfenol, Amorphous Tb-Fe based composites, Nanocrystalline Dy-Fe based composites. These materials are effective under a high bandwidth and at high operating temperature making them ideal for several applications. The best known giant magnetostrictive material, Terfenol-D, was developed in the 1950's at the Naval Ordinance Lab, USA. It is an alloy of Terbium, Iron, and Dysprosium. Some properties of Terfenol-D which is a composite from several published sources are presented in Table 2.

Properties	Terfenol-D
Energy Density, (kJm^{-3})	4.9-25
Effective Force in Terms of Mechanical Stress, (MPa)	5-70
Giant Magnetostriction, Strain, (ppm)	6000@150K, typical 800-2000
Bandwidth, (kHz)	<1
Hysteresis	~10%
Density, (kg/m^3)	9210-9250
Coupling factor, (-)	0.7-0.8
Young's Modulus, (GPa): at constant current at constant voltage	 18-55 50-90
Compressive Strength, (MPa)	304-880
Tensile Strength, (MPa)	28
Curie Temperature	380
Material Resistivity, (μΩm)	0.6
Piezomagnetic Constant (nm/A)	5-15
Relative Magnetic Permeability, (-)	2-10
Sound Propagation speed (m/s)	1650-1950

Table2. Properties of Terfenol-D.

A schematic representation of the *Villari effect* is depicted in Fig.2 [16]. In this way a magnetostrictive electric generator that utilizes vibrations to produce power can be designed. Three different sketches of MEG are shown in Fig. 3-5. Being incorporated into the structure of a controlled mechanical system, a MEG can also be used at the same time as a sensor for identification of the parameters of vibration and as a damper for vibration attenuation. A system with incorporated MEG can be called a mechanical system with active structure.

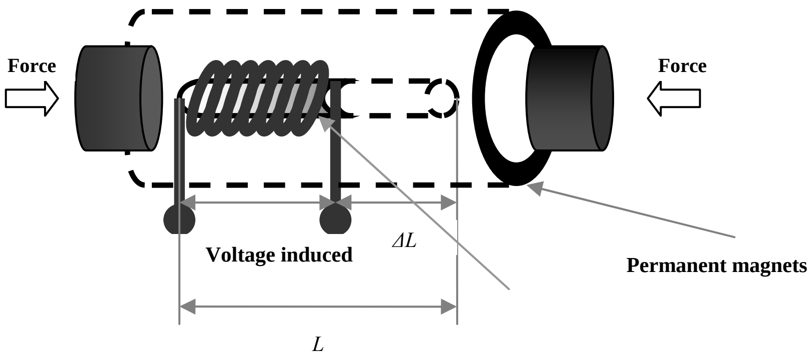

Figure 2. Schematic representation of the Villari effect.

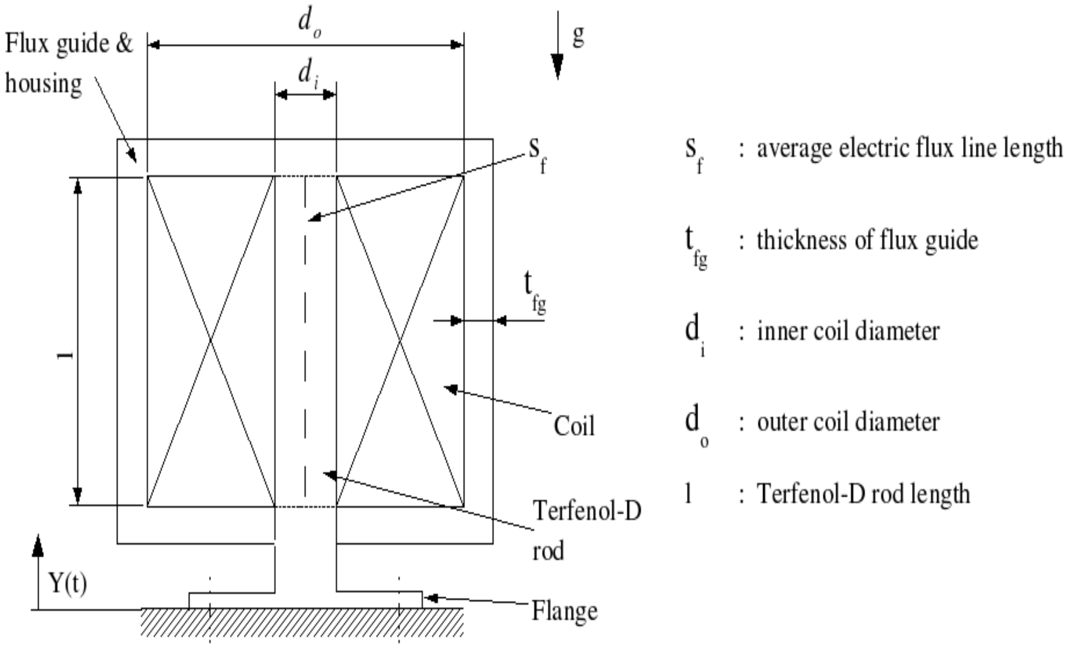

Figure 3. Schematic diagram of MEG integrated into a mechanical system by flange.

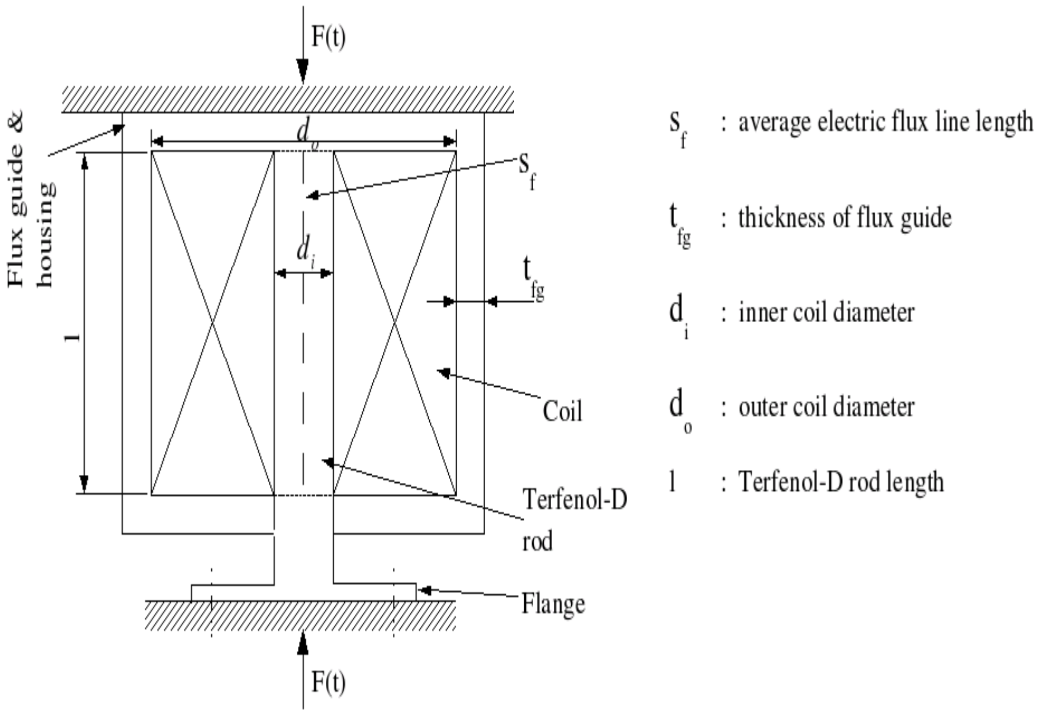

Figure 4. Schematic diagram of clamped arranged MEG.

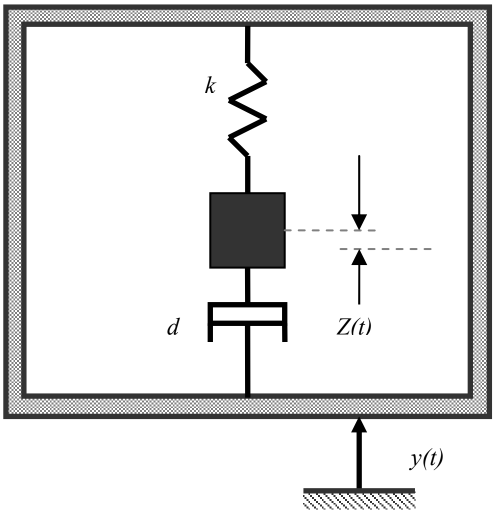

Figure 5. Schematic diagram of a seismic mass based generator.

The transduction process of the MEG work cycle can be studied from the upper part of Fig. 6 showing magnetostriction (strain) as a function of magnetic field intensity (*H*) and mechanical prestress [1]. A change in the mechanical strain comprises of magnetostrictive and ordinary Hook's strains and is a result of the combined response of prestressed active material to magnetic field strength. The Terfenol-D mechanical stress cycling output can be found in the coupled induction on the Fig. 6 (lower part) showing resulting (*B*-*H*) changes inducing voltage and energy in the generator coil winding. Change of the mechanical stress level in Terfenol-D results in coupled change in the magnetic induction (*B*). To counteract this change in *B* an electric current is induced in the coil creating a magnetic field (*H*). If the coil would to have zero resistance the magnetic induction *B* would not change. When the coil load is between zero and infinite resistance, electrical energy will be taken out of the MEG. For a given stress cycle input driven by vibrations, e.g. a vibrating surface, a continuous output of electrical energy can be maintained for some closed loop applications. The MEG takes out vibration energy from the stresses it is exposed to when the hosting system is vibrating and transforms the mechanical energy to electrical energy.

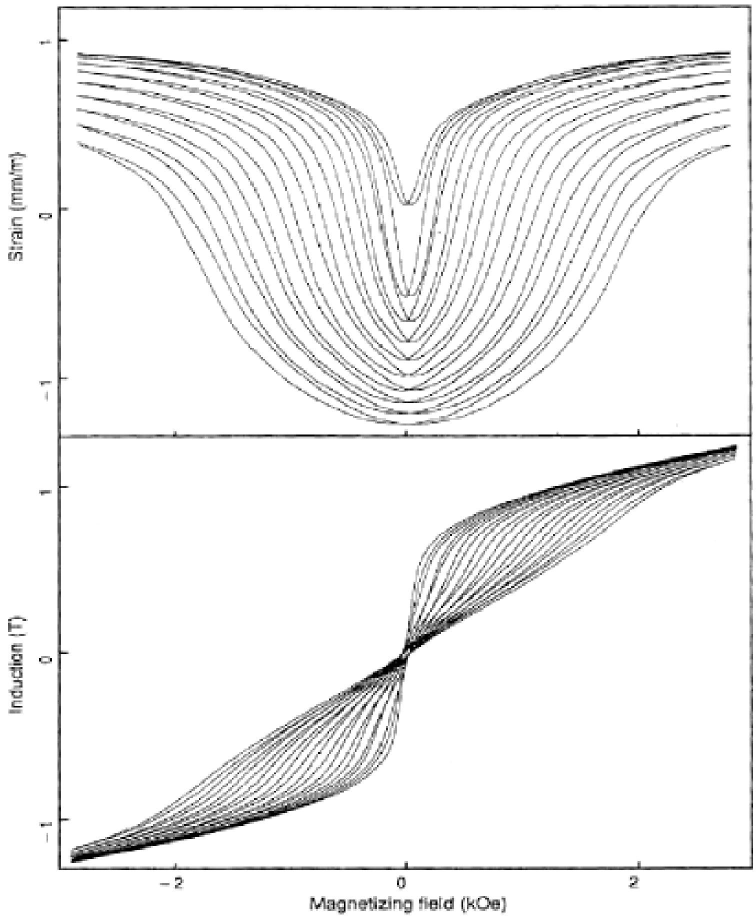

Figure 6. Typical magnetostriction and magnetic induction curves of magnetostictive material.

3. MATHEMATICAL MODEL OF A MECHANICAL SYSTEM WITH ACTIVE STRUCTURE

A set of rigid and/or flexible bodies connected by revolute, spherical and/or others joints, springs and/or dampers, with predefined internal and external constraints and restrictions imposed on their behaviour is called a *mechanical system*. If some elements of a mechanical system change the system stiffness and/or damping, and/or change the system functionality by exerting additional forces and/or torques as a response to applied electric or magnetic or temperature field, then such elements are called active ones. A mechanical system which comprises such elements is called a *mechanical system with active structure.*

An active structure (also known as *smart* or *adaptive* structure) has the ability to alter its configuration, form or properties as a response to changes in the environment. The term active structure also refers to the structures that, unlike traditional engineering structures, require constant motion and hence power input to remain stable. An example of an active structure is a set of elements comprising besides the load carrying elements also *sensors*, and/or *actuators,* and *processor/controller* [19].

A good real example of an adaptive structure is the human body where the skeleton carries a wide range of loads and the muscles change their configurations to do so. In the case of the human body, the sensory nerves are the sensors which gather information of the environment. The brain acts as the processor/controller to evaluate the information and decide to act accordingly and therefore instructs the muscles, which act as actuators to respond [19].

In engineering, there is already an emerging trend to develop active technology for ground and aircraft vehicles, machine tools and mechanisms by using smart materials based sensors and actuators for active vibrations and noise control. This is not the only possible application field where study of dynamics, control and optimization problems *for mechanical systems with active structure* is needed and is a great challenge.

3.1. Mathematical model of a mechanical system integrated with magnetostrictive electric generator

Consider a mechanical system having *n* degrees-of-freedom. Let the equations of controlled motion be:

$$\mathbf{A}(\mathbf{y})\ddot{\mathbf{y}} + \mathbf{C}(\mathbf{y},\dot{\mathbf{y}}) = \mathbf{u} \tag{1}$$

where $\mathbf{y} = (y_1, y_2, ..., y_n)$ be a vector of generalized coordinates, $\mathbf{u} = (u_1, u_2, ..., u_n)$ be a vector of the controlling stimuli (forces and/or torques), $\mathbf{A}$ and $\mathbf{C}$ be given matrices. Let be assumed that the system is integrated with a MEG and that the mass inertial parameters of the MEG are negligibly small compared to the mass inertia parameters of the whole mechanical system.

A characteristic property of magnetostrictive materials (active material in MEG) is that a mechanical strain will occur if they are subjected to a magnetic field in addition to strains originated from pure mechanically applied stresses. Also, their magnetization is changed with applied mechanical stresses in addition to the changes caused by varying applied magnetic field. These dependencies can be described by mathematical functions [1]:

$$\varepsilon = \varepsilon(\sigma, H) \tag{2}$$

$$B = B(\sigma, H) \tag{3}$$

where ε, σ, H be strain, stress and applied magnetic field strength, respectively, and B be magnetic flux density. Taking into account all above mentioned and the fact that the most important mode of operation of magnetostrictive materials is the longitudinal one, the linearization of the differential response of strain and magnetization (relations (2) and (3)) leads to the following equations of magnetomechanical coupling:

$$\varepsilon = S^H \sigma(\mathbf{y}, \dot{\mathbf{y}}) + d_{33} H \tag{4}$$

$$B = d_{33}^* \sigma(\mathbf{y}, \dot{\mathbf{y}}) + \mu^\sigma H \tag{5}$$

Here:

$S^H = \frac{\partial \varepsilon}{\partial \sigma}_{|H=const} = \frac{1}{E^H}$, where E^H be Young's modulus at constant applied magnetic field strength;

$d_{33} = \frac{\partial \varepsilon}{\partial H}_{|\sigma=const}$ be the magnetostrictive strain derivative (linear coupling coefficient);

$d_{33}^* = \frac{\partial B}{\partial \sigma}_{|H=const}$ be the parameter of magnetomechanical effect;

$\mu^\sigma = \frac{\partial B}{\partial H}_{|\sigma=const}$ be magnetic permeability at a constant stress.

In equations (4), (5) the stress $\sigma(\mathbf{y}, \dot{\mathbf{y}})$ characterizes the interaction between the dynamics of the mechanical system (hosting system) and the dynamics of MEG. Below it will be assumed the following

$$\sigma(\mathbf{y}, \dot{\mathbf{y}}) = f(\mathbf{y}, \dot{\mathbf{y}}, \mathbf{c}) \tag{6}$$

where function $f(\mathbf{y}, \dot{\mathbf{y}}, \mathbf{c})$ and vector parameter **c** are determined by the given magnetic design of a MEG and by the design of an adaptive structure that is needed to integrate the transducer into a hosting mechanical system.

Several important assumptions are built into the magnetostrictive model (equations (4), (5)). First, linear operation of the active material (Terfenol-D [1]) in the magnetostrictive transducer is assumed. Although the magnetostrictive effect is nonlinear, for low signal levels, less than approximately one-third of the maximum strain capability, the linear equations of magnetostriction provide a good first approximation [20]. Second, the magnetostriction process is assumed to be reversible according to

$$d_{33} = \frac{\partial \varepsilon}{\partial H}_{|\sigma=const} = \frac{\partial B}{\partial \sigma}_{|H=const} = d_{33}^* \tag{7}$$

Finally, strain, stress, *H,* and *B* are assumed to be uniform throughout the active material. Note that it's not necessary to assume the coefficients $E^H, \mu^\sigma, d_{33}, d_{33}^*$ single valued or linear, however this is generally the approach taken in many investigations of performance of magnetostrictive transducers [20].

Equations (1) - (7) constitute the mathematical model of a mechanical system with active structure namely a controlled mechanical system integrated with magnetostrictive electric generator. As indicated in (4)-(6), it is assumed that the stress σ depends on the phase state of the mechanical system $(\mathbf{y}, \dot{\mathbf{y}})$, i.e. the dynamics of the hosting system affects the performance of the magnetostrictive transducer.

3.2. Mathematical model of a mechanical system integrated with piezoceramic electric generator

Another well-known active material, piezoceramics, can also be used for creation of a device for vibration-to-electric energy conversion. The mathematical model of a mechanical system with active structure modeling a controlled mechanical system integrated with piezoceramic electric generator can be developed in the same way as in case of above considered MEG. Piezoelectric transducer behavior is determined by the interrelation of electrical and mechanical magnitudes. They can be described with linear relations between electrical and mechanical variables as a good approximation for sensor and as a first approximation for actuator applications:

$$\varepsilon = S^E \sigma(\mathbf{y}, \dot{\mathbf{y}}) + d_{11} E_{el} \tag{8}$$

$$D_{el} = d_{11}^{*} \sigma(\mathbf{y}, \dot{\mathbf{y}}) + \varepsilon^{\sigma} E_{el} \tag{9}$$

Here:

$S^E = \frac{\partial \varepsilon}{\partial \sigma}_{|E_{el}=const} = \frac{1}{E^{E_{el}}}$, where $E^{E_{el}}$ be Young's modulus at constant applied electrical field intensity;

$d_{11} = \frac{\partial \varepsilon}{\partial E_{el}}_{|\sigma=const}$ be the piezoelectric coefficient (linear coupling coefficient);

$d_{11}^{*} = \frac{\partial D_{el}}{\partial \sigma}_{|E_{el}=const}$ be parameter of electromechanical effect;

$\varepsilon^{\sigma} = \frac{\partial D_{el}}{\partial E_{el}}_{|\sigma=const}$ be dielectricity constant at constant mechanical stress;

E_{el}, D_{el} are electrical field intensity and electrical displacement, respectively.

In equations (8), (9) the stress $\sigma(\mathbf{y}, \dot{\mathbf{y}})$ characterizes the interaction between the dynamics of the mechanical system (hosting system) and the dynamics of the piezoceramic electric generator.

Magnetostrictive materials and piezoelectric ceramics change mechanical energy into electric energy and vice versa. Because of the inversive of magnetostrictive and piezoelectric effects these smart materials can be used for actuators, sensors and generators. This multifunctional property of smart materials is important for adaptronic systems [21]. The spatial and functional integration of sensor/generator, actuator and controller into a mechanical system and mathematical description of the performance of the obtained controlled system with active structure are in most general cases great challenges. One possible approach for development of this kind of mathematical models can probably be the approach which was used for modelling and optimisation of the semi-passively actuated multibody systems described in [22, 23].

4. INVERSE DYNAMICS FOR A MECHANICAL SYSTEM WITH MAGNETOSTRICTIVE ELECTRIC GENERATOR

The developed above mathematical models of controlled mechanical systems with active structure can be used for many applications. For instance, to solve inverse dynamics problems for controlled mechanical systems integrated with magnetostrictive or piezoelectric transducers (actuators, sensors, electric generators).

Consider the following problem.
Problem A. Let the motion of a controlled mechanical system (1) integrated with magnetostrictive transducer (4)-(7) be given, that is the time history of generalized coordinates be prescribed:

$$\mathbf{y} = \mathbf{y}_a(t), \qquad t \in [0, T] \tag{10}$$

where T be the duration of controlled motion of the system in question.

It is required to determine the control stimuli $\mathbf{u}(t)$ that is necessary to perform the prescribe motion (10), the voltage $U(t)$ induced in coil surrounding the Terfenol-D sample, and the strain $\varepsilon(t)$ in an active material of the magnetostrictive transducer.

A solution of *Problem A* can be obtained by following the procedure which was described early in [23].
Using equations of motion (1) the control stimuli $\mathbf{u}(t)$ needed for prescribed motion (10) can be calculated by the formula

$$\mathbf{u}_a(t) = \mathbf{A}(\mathbf{y}_a(t))\ddot{\mathbf{y}}_a(t) + \mathbf{C}(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t)) \tag{11}$$

For given magnetic design and adaptive structure of magnetostrictive transducer (function $f(\mathbf{y}, \dot{\mathbf{y}}, \mathbf{c})$), the stress applied to active material during the prescribe motion $\mathbf{y} = \mathbf{y}_a(t), \quad t \in [0, T]$ of the hosting system is determined by expression:

$$\sigma(\mathbf{y}, \dot{\mathbf{y}}) = \sigma(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t)) = f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c}) \tag{12}$$

Using equations (4), (5), (12), Faraday's law and Ohm's law the induced voltage $U(t)$ and the strain $\varepsilon(t)$ in the magnetostrictive transducer are determined by the following expressions:

$$U(t) = -NAf_a(t) + cNAe^{-ct}[B_0 + \int_0^t f_a(\tau)e^{c\tau}d\tau] \tag{13}$$

$$\varepsilon(t) = \frac{1}{E^H} f(\mathbf{y}_a(t), \dot{\mathbf{y}}_a(t), \mathbf{c}) + d_{33}(H_0 - \frac{1}{c\mu^\sigma}(f_a(t) - cB(t)) \tag{14}$$

Here in (13), (14) N and A are the number of turns and the cross section area of coil, $B_0 = B(0)$ is initial magnetic flux, H_0 is a steady bias magnetic field.

Magnetic flux is determined by the following expressions:

$$B(t)=e^{-ct}(B_0+\int_0^t f_a(\tau)e^{c\tau}d\tau) \qquad (15)$$

$$c=Rl/(\mu^\sigma N^2 A), \qquad f_a(t)=c(\mu^\sigma H_0+d_{33}^* f(\mathbf{y}_a(t),\dot{\mathbf{y}}_a(t),\mathbf{c})) \qquad (16)$$

where l is the coil length, $R=R_0+r$, R_0 is the electric circuit load and r is the coil resistance.

So, the inverse dynamics problem for the controlled mechanical system integrated with magnetostrictive transducer has been solved.

5. MODELING OF MAGNETOSTRICTIVE ELECTRIC GENERATOR

Several results on modeling of the developed MEG within linear models have been published earlier in [24, 25]. Below some of the latest results on modeling of the performance of MEG obtained by implementation of the above described inverse dynamics algorithm are presented. The algorithm has been implemented for two cases. The first case (Model 1 or *linear model*) corresponds to a MEG model with constant material parameters, namely the Young's modulus at constant applied magnetic field strength, the magnetic permeability at a constant stress, and the linear coupling coefficient are supposed to be constant during operation of MEG. The second case (Model 2 or *nonlinear model*) corresponds to a MEG model with constant Young's modulus at constant applied magnetic field strength but with varying magnetic permeability and linear coupling coefficient.

The input stress excitation was chosen as $\sigma=-\left[\sigma_0+a\sin\left(2\pi ft\right)\right]$. The parameter values $\sigma_0^{low}=15$ MPa, $a_{low}=10$ MPa were considered to be low level excitation and the parameter values $\sigma_0^{high}=25$ MPa, $a_{high}=20$ MPa were considered to be high level excitation.

The parameters of Terfenol-D rod and coil were as follows:

$$d_{coil}=16.2\text{ mm}, \quad l=l_{Terfenol}=l_{coil}=50\text{ mm}, \quad A=A_{coil}=\pi\frac{d_{coil}{}^2}{4}, \quad d_{Terfenol}=15\text{ mm}$$

Young's modulus of the Terfenol-D rod at constant applied magnetic field strength: $E^H=25$ GPa.

The following values of the electric and magnetic parameters were used:

$$Z_{eq}^1=Z_{eq}(1,r,C_*)\text{ and }Z_{eq}^0=Z_{eq}(1,r,0), \quad Z_{eq}(R_0,r,C)=\left(R_0+r\right)+j\left(\omega L_{coil}-\frac{1}{\omega C}\right)$$

$$C_*=\frac{1}{\omega^2 L_{coil}}, \quad \omega=2\pi f \qquad B_0=d_{33}\sigma\left(t=0\right)+\mu^\sigma H_0$$

$$r=0.66\ \Omega \qquad N=116$$

$$L_{coil}=362\ \mu\text{H} \qquad 3.77\cdot10^{-6}\ \frac{\text{N}}{\text{A}^2}<\mu^\sigma<1.76\cdot10^{-5}\ \frac{\text{N}}{\text{A}^2}$$

$$\text{H}_0=54.1\ \frac{\text{kA}}{\text{m}} \qquad 8.60\cdot10^{-3}\ \frac{\mu\text{m}}{\text{A}}<d_{33}<2.12\cdot10^{-2}\ \frac{\mu\text{m}}{\text{A}}$$

Some results of modeling of the electrical power output as a function of frequency for two cases of load and for two different levels of excitation are presented in Table 3. The results are also depicted in Fig. 7- 8. The mean electrical power output was calculated using the following expression:

$$P_{out} = \frac{1}{T}\int_0^T \frac{U^2(t)}{\left|Z_{eq}\right|^2} R_0 dt \quad (17)$$

Model 1	Low excitation		High excitation		**Model 2**	Low excitation		High excitation	
***f* [Hz]**	Z_{eq}^1	Z_{eq}^0	Z_{eq}^1	Z_{eq}^0	***f* [Hz]**	Z_{eq}^1	Z_{eq}^0	Z_{eq}^1	Z_{eq}^0
50	0,44	0,44	1,53	1,53	**50**	0,45	0,44	1,55	1,54
100	1,65	1,62	5,79	6,69	**100**	1,76	1,73	6,05	5,94
150	3,38	3,26	11,96	11,54	**150**	3,88	3,72	13,08	12,58
200	5,34	5,06	19,06	18,03	**200**	6,69	6,25	22,03	20,66
250	7,31	6,79	26,29	24,36	**250**	10,08	9,12	32,20	29,37
300	9,14	8,34	33,13	30,12	**300**	13,91	12,14	42,90	38,05
400	12,17	10,79	44,68	39,37	**400**	22,33	18,10	63,81	53,74
500	14,38	12,49	53,30	45,91	**500**	30,98	23,42	82,04	66,27
750	17,54	14,80	65,88	54,93	**750**	49,71	32,92	113,37	85,76
1000	19,00	15,82	71,83	58,99	**1000**	62,53	38,32	130,35	95,46

Table 3. Power output versus frequency for two load configurations, Z_{eq}^1, Z_{eq}^0, and two excitation levels for Model 1 and Model 2

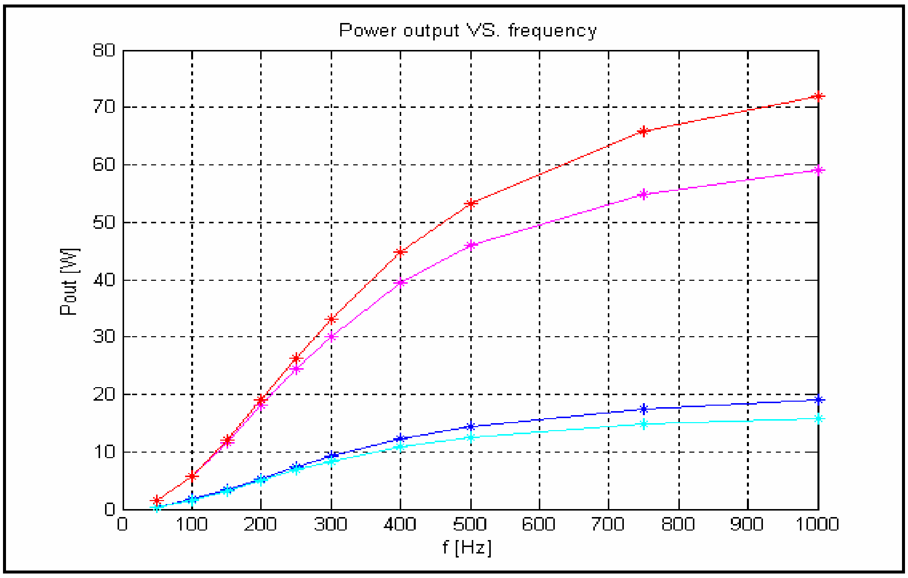

Figure 7. Model 1 – Power output versus frequency for the two load configurations (blue-magenta and cyan-red) and the two excitation levels (blue-cyan and magenta-red).

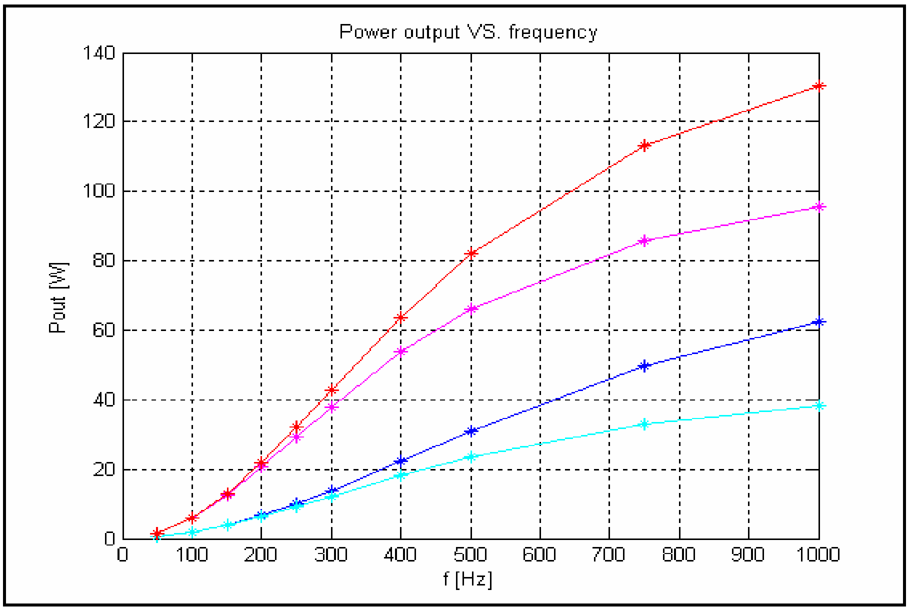

Figure 8. Model 2 – Power output versus frequency for the two load configuration (blue-magenta and cyan-red) and the two excitation levels (blue-cyan and magenta-red).

6. EXPERIMENTAL STUDY OF MAGNETOSTRICTIVE ELECTRIC GENERATOR

A MEG was manufactured and installed at Chalmers University of Technology. It has a laminated Terfenol-D rod with length l=50 mm and diameter d=15 mm as core element. Permanent magnets (TBD alloy) are used to create magnetic bias field for the Terfenol-D rod. The magnets are round shaped with diameter 6 mm and height 2.5 mm. Due to design restrictions the maximum number of magnets that can be used is 320. The Terfenol-D rod is fitted into a bobbin which has the transformer coil wound around it. A change in magnetic field will result in induced electric current in this coil. The MEG is shown in Fig. 9.

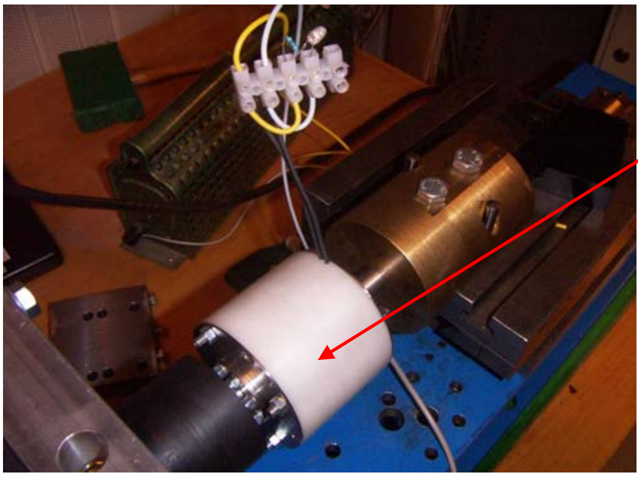

Figure 9. Chalmers Magnetostrictive Electric Generator.

The test rig with MEG, amplifier, oscilloscope (HP, 4 channel 100 MHz), data acquisition unit and frequency converter was set up. It is depicted in Fig. 10.

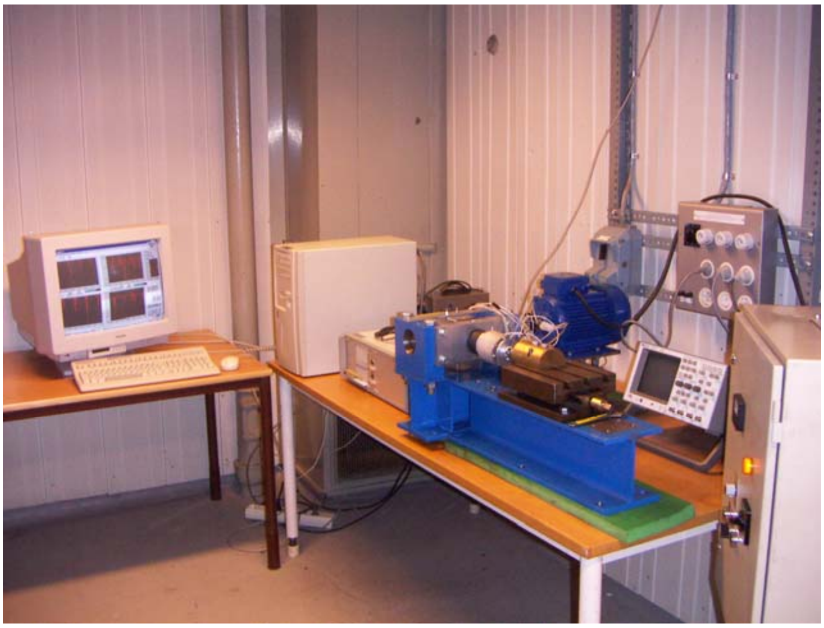

Figure 10. Setup for experimental study of performance of Chalmers Magnetostrictive Electric Generator.

The test rig is used for high frequency vibration excitation of the MEG via a cam coupled to an electric motor. The facet on the cam profile was machined to give a sinus-like wave input to the MEG. The speed of the motor, giving frequency of external excitation to the MEG, is controlled by an electrical frequency converter. A Chalmers built force sensor (4 strain gauges) is used to measure the mechanical force input to the MEG. The wiring arrangement of the force sensor is a Wheatstone bridge which is connected to the amplifier. The data of the force and voltage can be obtained with the oscilloscope and with the data acquisition unit. The output of MEG is an AC voltage.

In Fig. 11-13 the time histories of measured voltage and calculated voltage obtained by using Model 1 are presented. These curves correspond to excitation frequency f = 500 Hz, electrical load R_0 = $1\,\Omega$, but to different values of mechanical prestress σ_0. Electrical power output P_{out} was evaluated by using formula (17) for both measured data, $P_{out}^{\exp}$, and for data obtained by simulation within Model 1, P_{out}^{mod}. The following values of power output were obtained:

$$P_{out}^{\exp} = 21{,}67W, \quad P_{out}^{\mathrm{mod}} = 22{,}22W, \quad \text{for } \sigma_0 = 10{,}18MPa \tag{18}$$

$$P_{out}^{\exp} = 6{,}17W, \quad P_{out}^{\mathrm{mod}} = 9{,}27W, \quad \text{for } \sigma_0 = 5{,}84MPa \tag{19}$$

$$P_{out}^{\exp} = 2{,}03W, \quad P_{out}^{\mathrm{mod}} = 3{,}47W, \quad \text{for } \sigma_0 = 2{,}46MPa \tag{20}$$

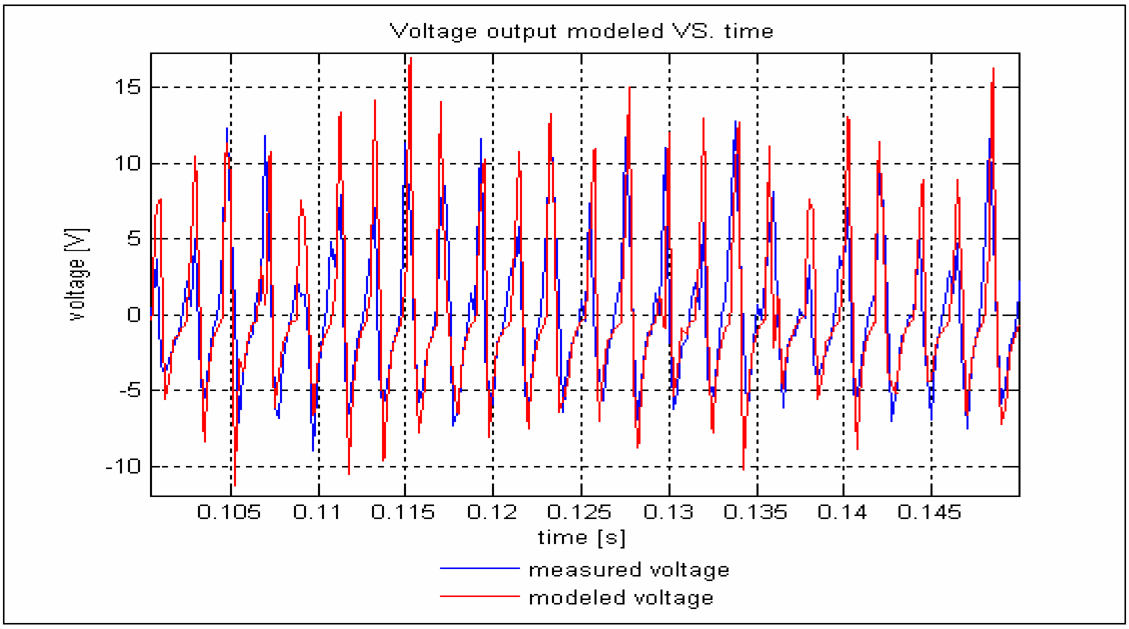

Figure 11. Time histories of measured and calculated voltages for f = 500Hz, $\sigma_0 = 10{,}18 MPa$, *and electrical load* R_0 *= 1 Ohm,* μ^{σ} *= 1,39E-05N/A,* μ_r *= 11,1,* d_{33} *= 1,50E-08 m/A,* k_{33} *= 0,75.*

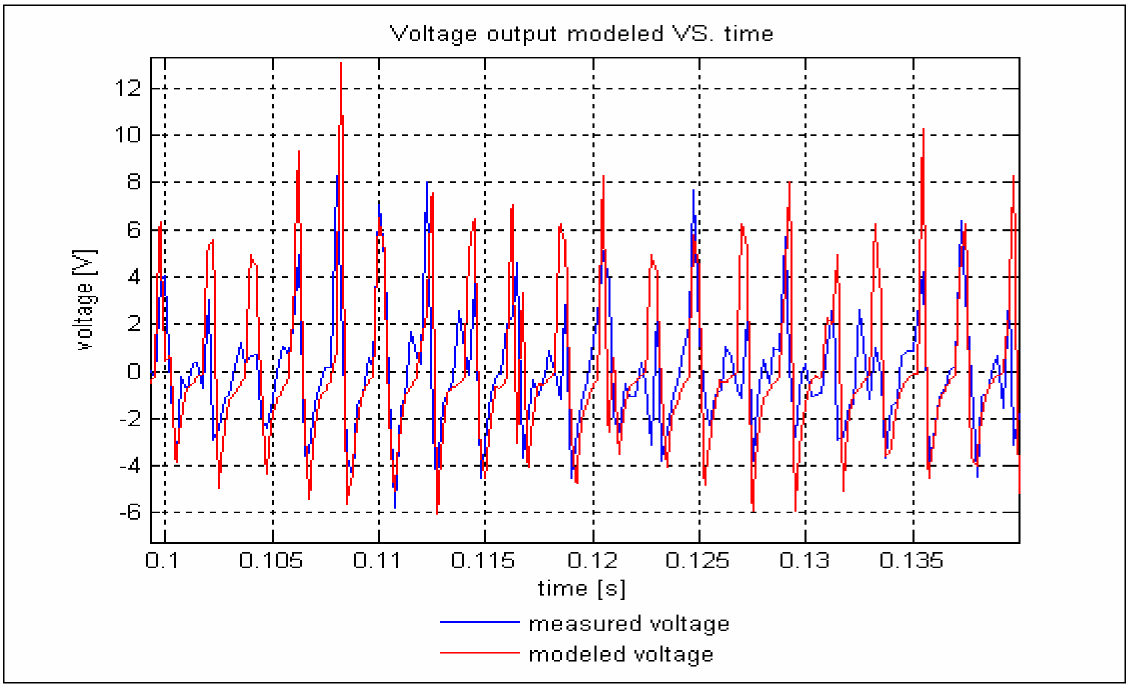

Figure 12. Time histories of measured and calculated voltages for f = 500Hz, $\sigma_0 = 5{,}84 MPa$, *and electrical load* R_0 *= 1 Ohm,* μ^{σ} *= 1,40E-05N/A,* μ_r *= 11,1,* d_{33} *= 1,50E-08 m/A,* k_{33} *= 0,75.*

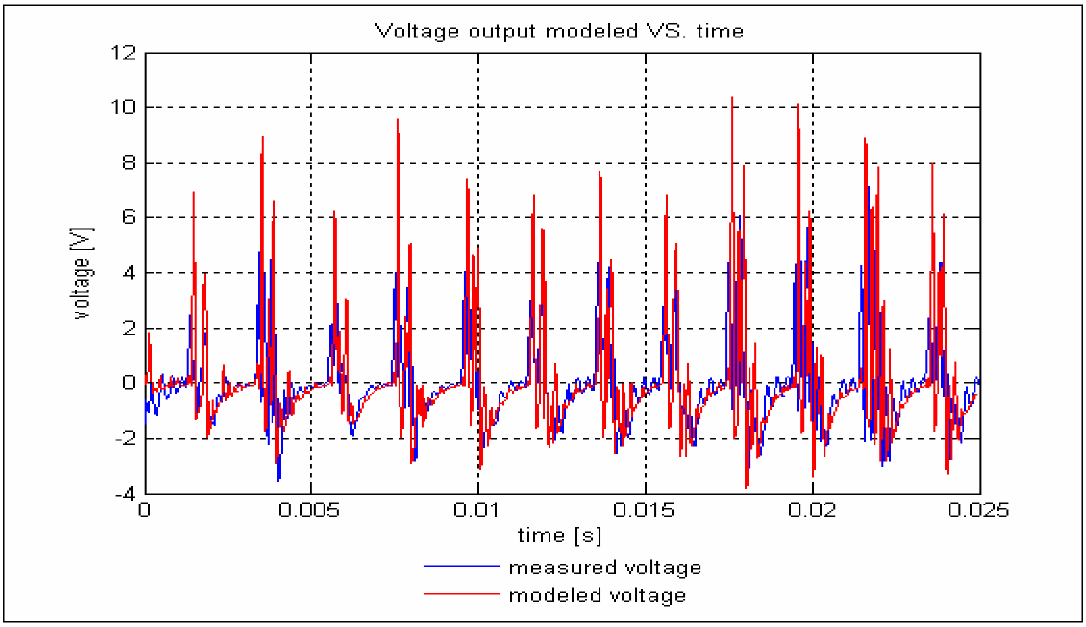

Figure 13. Time histories of measured and calculated voltages for f = 500Hz, $\sigma_0 = 2{,}46MPa$, *and electrical load* R_0 *= 1Ohm,* μ^σ *= 1,37E-05N/A,* μ_r *= 10,9,* d_{33} *= 1,48E-08 m/A,* k_{33} *= 0,75.*

7. CONCLUSIONS

In the paper some theoretical and experimental results of the study of the MEG which was built at the Department of Applied Mechanics, Chalmers University of Technology have been presented. Brief fundamentals needed for designing of magnetostrictive generators have been outlined and several schematic diagrams of these transducers have been sketched.

Incorporation of one or more MEG into mechanical system makes it a so-called mechanical system with active structure. Two mathematical models have been developed which are suitable for simulation of mechanical systems with active structure, in the current case for mechanical systems integrated with magnetostrictive transducers and mechanical systems integrated with piezoceramic transducers.

In the paper the inverse dynamics problem for controlled mechanical system with MEG has been considered. An algorithm for solving the problem has been described. This algorithm gives possibility to determine the voltage induced in the coil surrounding the Terfenol-D sample and the strain in the sample for given external excitation. Analysis of simulation results has shown that electric power output of MEG is sensitive with respect to electrical load, frequency and level of external periodic excitations (for details see Fig. 7- 8 and Table 3).

Several experiments have been conducted with developed physical prototype of MEG using test rig depicted in Fig. 10. A comparison of the obtained experimental data and respective model output data (see data in (18) - (20) for power output and plots in Fig. 11-13 for voltage) shows that experimental and simulation data are in reasonable proximity. This is valuable evidence for validation of the developed mathematical models of magnetostrictive electric generator.

Both simulation results and experimental data have confirmed functionality of the designed MEG using giant magnetostrictive material Terfenol-D. A video showing the Chalmers built MEG in operation can be seen via web link http://www.mvs.chalmers.se/~berbyuk/chalmers_meg_050404.MOV

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